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FAR-ULTRAVIOLET IMAGING OF THE GLOBULAR CLUSTER NGC 7099 WITH THE SECOND WIDE-FIELD AND PLANETARY CAMERA[1]

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ABSTRACT

We have imaged the globular cluster NGC 7099 in the far-UV and visible with WFPC2 on the *Hubble Space Telescope.* Our far-UV images show a sparsely populated and fully resolved central region. The far-UV to visible color–magnitude diagram of these stars shows a well-defined horizontal branch with no evidence for hot, more evolved descendants. We find one hot horizontal branch star; the center of the cluster harbors four luminous blue stragglers. Far-UV images do not show any singularly steep density gradient at small radii among the horizontal branch stars of this post–core-collapse cluster.

Subject headings: globular clusters: individual (NGC 7099) — stars: evolution — stars: horizontal-branch — ultraviolet: stars

1. INTRODUCTION

The post–horizontal-branch evolution of low-mass stars remains to be clearly understood (Dorman, Rood, & O'Connell 1993) and is complicated by the possible effects of stellar interactions in the high-density regions of globular clusters (Djorgovski & Piotto 1992). Stars in these very late stages are likely to be the principal contributors to the far-UV excess in early-type galaxies (Dorman, O'Connell, & Rood 1995).

In this paper we add a second "post–core-collapse" cluster to our first far-UV observations of NGC 6681 (Watson et al. 1994) with the second Wide Field and Planetary Camera (WFPC2) on the *Hubble Space Telescope.* We present a photometric study of hot stars in the cluster NGC 7099 (M30) and discuss our results in terms of the structure of the hot horizontal branch (HB) in a far-UV to visible color–magnitude diagram and the radial profile of the cluster. We have previously noted the complementary nature of WFPC2 observations to those of the Ultraviolet Imaging Telescope.

NGC 7099 is a prototypical "post–core-collapse" cluster, whose radial profile is thought to be better characterized by a power law than a King model (Djorgovski & King 1984). It is located at a distance of about 7.5 kpc, about 6.8 kpc from the Galactic center, has a low reddening with $E_{B-V} = 0.05$, and has low metallicity with $[Fe/H] = -2.13$ (Djorgovski 1994; Zinn 1985).

Yanny et al. (1994) have observed the cluster with WFPC2 and present color magnitude diagrams in the standard *HST* filters. They put an upper limit of 2''.5 on the size of any flat core that might be substituted for the power law. They note a high incidence of blue stragglers in the center of the cluster.

2. OBSERVATION, REDUCTIONS, PHOTOMETRY, AND CALIBRATION

Exposures of length 2 × 1200 and 2 × 800 s in F160BW and 10 and 100 s in F555W) were obtained on 1994 October 10. The cluster center was located on PC1. Burrows (1995) and Trauger et al. (1994) describe the instrument in more detail. Watson et al. (1994) have addressed the imaging and transmission properties of F160BW. For further information on these matters we draw the reader's attention to Clarke et al. (1996), who detail the F160BW PSF (FWHM 0''.1), prism distortion and contamination effects. The images were reduced following Holtzman et al. (1995b). The two F160BW images were combined using a standard cosmic-ray rejection algorithm, and the central 18''.4 × 18''.4 of the cluster is shown in Figure 1 (Plate 18). The reader will find Figure 3 of Yanny et al. a particularly useful accompaniment to this paper.

Following Watson et al. (1994) and Holtzman et al. (1995a) we use $m \equiv -2.5 \log \langle f_\lambda \rangle - 21.1$ and the units of $\langle f_\lambda \rangle$ are ergs s^{-1} cm^{-2} Å^{-1}. This is described as the STMAG system by Holtzman et al. (1995a), and the zero points are 13.682 and 21.688 in the UV and visible, respectively. WFPC2 underwent a standard decontamination on 1994 September 24, 16 days prior to our observations. We have corrected our m_{160} magnitudes by 0.19 mag, following equation (1) of Holtzman et al. (1995a) and the contamination rate given for chip 1. A charge transfer efficiency correction was made to the magnitudes of 0.04 mag at row 800, tapering to zero at row 1 of each chip.

If we assume mean wavelengths in the filters of 1500 and 5550 Å and a $R_V = 3.2$ reddening law from Cardelli, Clayton, & Mathis (1989), the interstellar reddening corre-

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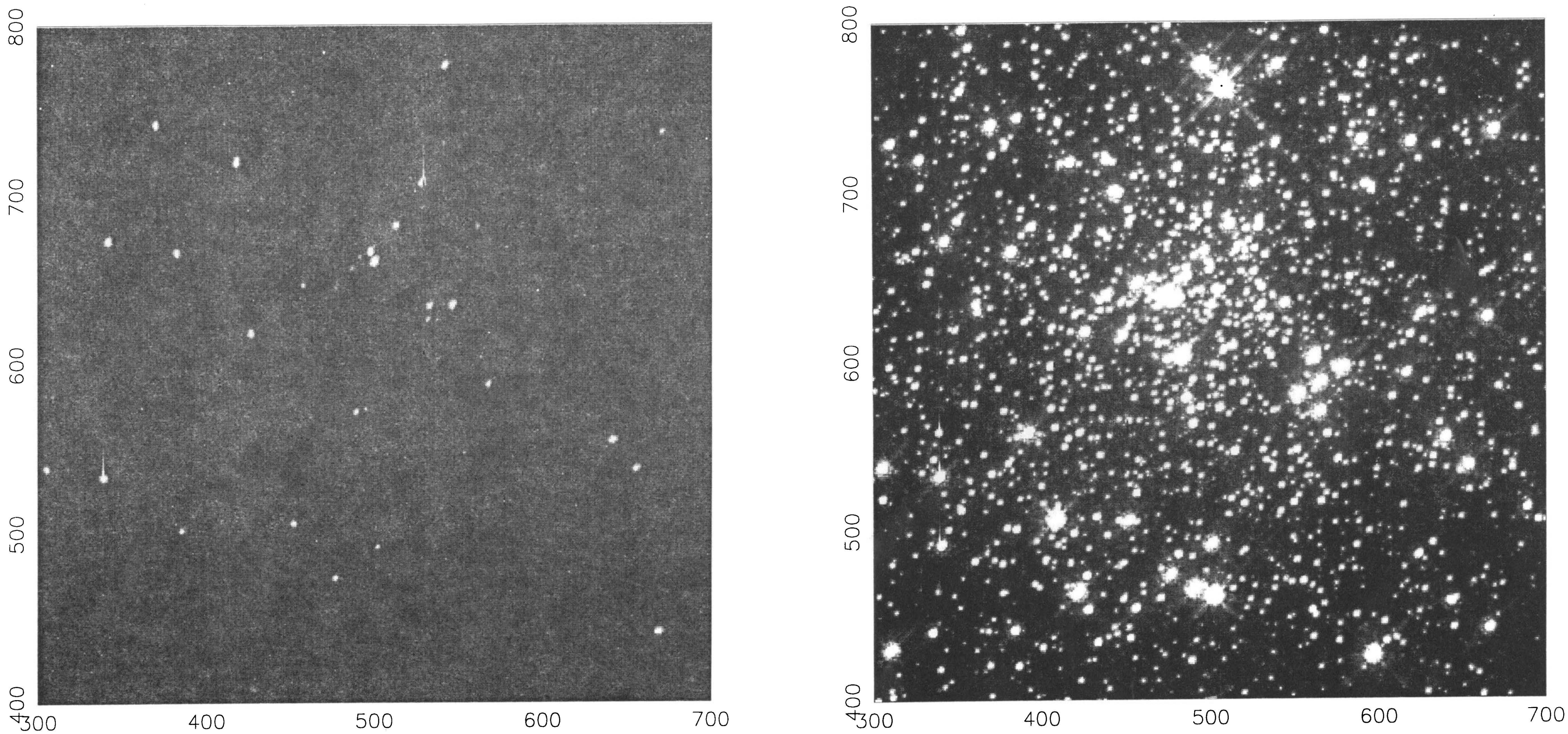

FIG. 1.—Far-UV F160BW (*left*) and visible F555W (*right*) images of the center of NGC 7099. The images are 18″.4 to a side at a pixel scale of 0″.046. The rotation between these and celestial coordinates is 110°.2, with north roughly to the right and east roughly vertical.

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sponds to $A_{160} = 0.44$ and $A_{555} = 0.16$. If the reddening to the cluster is nonstandard, A_{160} may differ from this value. With the currently accepted distance modulus of 14.35 ± 0.15, we obtain $(m - M)_{160} = 14.79$.

A total of 93 stars were found in the combined F160BW images. Aperture photometry was performed using a 0\".14 radius aperture in the PC and a 0\".2 radius aperture in the WF. Appropriate aperture corrections were made to the 0\".5 standard adopted by Holtzman et al. (1995a). Chromatic aberration is present in the ultraviolet images obtained with WFPC2. We therefore tested the radial dependence of the aperture correction. An upper limit to position-dependent systematic errors in the UV is 0.05 mag.

A far-UV to visible color–magnitude diagram (CMD) of NGC 7099 is shown in Figure 2. The most striking feature of the CMD is the HB. We have carefully checked the outliers and have confirmed their reality. We believe that the CMD is complete to $m_{160} \approx 18$, at which point the stars become confused with noise resulting from cosmic-ray events and the photometric errors exceed 0.3 mag. This limit is marked with a dashed line in the CMD. Photometry from chip 1 only is recorded in Table 1. In the table the (x, y) coordinates are those of Figure 2. Column (4) gives $m_{160} - m_{555}$; columns (5) and (6) record m_{160} and the uncertainty in the color, respectively.

3. THE HORIZONTAL BRANCH

On the Kurucz (1991) temperature scale the hottest star in the present CMD has $T_{\rm eff} \approx 20{,}000$ K, which corresponds to an envelope mass, $M_{\rm env} \approx 0.035\ M_\odot$ in the most metal-poor models of Dorman et al. (1993). Helium main-sequence stars (subdwarf O stars in the notation of Greenstein & Sargent 1974) are absent from this cluster. The lack of stars brighter than $m_{160} = 14.0$ is a constraint on post-HB stellar evolution, as we do not detect AGB-manqué (Greggio & Renzini 1990), post–early-AGB (Brocato et al. 1990), or post-AGB stars. The likely pregenitors of AGB-manqué and post–early-AGB stars are extreme-HB stars in the nomenclature of Dorman et al. (1993). Therefore, our failure to detect hot descendants of HB stars is consistent with our detection of only one HB star with $T_{\rm eff} > 16{,}000$ K and the very short evolutionary timescales of post-AGB stars.

Also shown on the CMD is the locus for a model ZAHB with [Fe/H] = -2.26 from Dorman et al. (1993), kindly provided by Dorman (1995). Magnitudes were generated from Kurucz (1991) model atmospheres and the response curves of Holtzman et al. (1995a) and are recorded in Table 2. As in the case of NGC 6681 (Watson et al. 1994), the calculated HB is brighter than most of the observed HB stars, but it is unclear at present whether this is a calibration or a distance modulus problem. From Figure 2 of Yanny et al. (1994) one can readily appreciate the difficulty of measuring a distance modulus from an optical CMD. Strengthening the calibration of the FUV CMD potentially offers a more reliable distance (but see Whitney et al. 1994, and references therein.)

4. BLUE STRAGGLERS

The CMD shows four stars at $m_{160} - m_{555} \approx -1$ between 0.8 and 2.2 mag fainter than the HB at that color. These are stars 12, 21, 27, and 28 in Table 1. We have examined the original frames and conclude that these stars are indeed real. Yanny & Schneider (1995) have identified these stars for us on their *UBV* frames of NGC 7099, and Figure 3, which they have kindly provided from Yanny et al. (1994), indicates that three of these stars are among the hottest and most luminous blue stragglers they have observed.

Blue stragglers are normally associated with the core hydrogen burning stage of stellar evolution. Indeed, even the brightest of these four stars are not far outside the range of excess luminosity over the turnoff luminosity, which might be expected from the merger of two 0.7 $M_\odot$ stars in

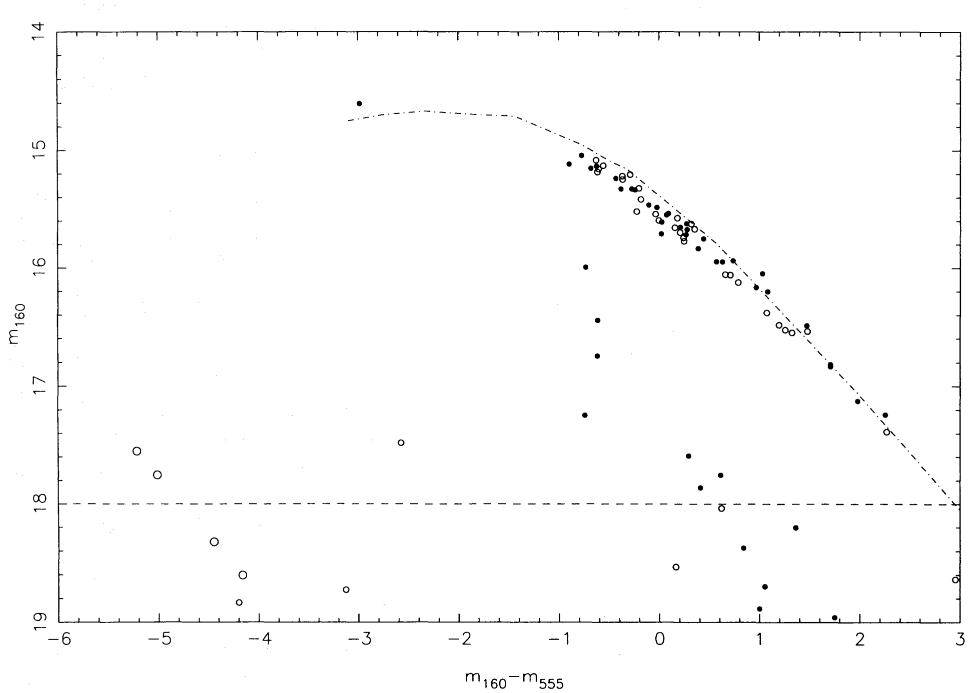

FIG. 2.—Far-UV to visible color-magnitude diagram for NGC 7099. The approximate limiting magnitude $m_{160} \approx 18$ is marked with a dashed line. Stars shown in Fig. 1 (PC) are denoted by solid symbols; other symbols identify stars from the WF chips.

TABLE 1

PHOTOMETRY OF NGC 7099

Star (1)	x (2)	y (3)	160–555 (mag) (4)	160 (mag) (5)	Error (mag) (6)
1.......	55	193	−0.10	15.47	0.04
2.......	665	212	1.47	16.49	0.08
3.......	503	262	−0.27	15.33	0.04
4.......	758	271	0.57	15.95	0.05
5.......	511	296	0.61	17.76	0.22
6.......	199	349	0.28	15.67	0.04
7.......	596	391	−0.24	15.34	0.04
8.......	666	441	−0.77	15.04	0.03
9.......	709	461	1.36	18.20	0.30
10......	476	473	0.97	16.17	0.06
11......	501	491	1.71	16.82	0.10
12......	385	500	−0.62	16.74	0.10
13......	451	504	0.63	15.95	0.05
14......	352	511	1.72	19.28	0.60
15......	566	515	1.00	18.89	0.48
16......	339	531	0.02	15.61	0.04
17......	305	537	0.74	15.94	0.05
18......	653	536	0.39	15.84	0.05
19......	552	546	0.84	18.37	0.34
20......	639	553	−0.02	15.49	0.04
21......	488	570	−0.61	16.44	0.08
22......	494	572	0.41	17.86	0.08
23......	566	586	1.08	16.20	0.06
24......	536	602	1.06	18.70	0.45
25......	426	616	0.07	15.55	0.04
26......	469	619	1.39	19.18	0.63
27......	530	624	−0.74	17.25	0.14
28......	531	632	−0.73	15.99	0.06
29......	544	633	−0.62	15.13	0.03
30......	457	645	2.25	17.24	0.14
31......	485	655	0.29	17.59	0.19
32......	499	658	−2.99	14.61	0.02
33......	382	664	0.21	15.65	0.04
34......	496	664	−0.90	15.12	0.03
35......	342	671	−0.38	15.33	0.04
36......	511	680	0.44	15.75	0.05
37......	292	701	−0.43	15.24	0.03
38......	527	705	0.02	15.71	0.05
39......	417	717	−0.68	15.16	0.03
40......	668	735	1.71	16.83	0.10
41......	370	739	0.27	15.62	0.04
42......	596	745	1.75	18.96	0.55
43......	276	746	0.27	15.72	0.05
44......	271	791	1.98	17.12	0.13
45......	646	106	1.3:	16.49	0.08
46......	611	387	1.2:	16.43	0.08
47......	498	394	1.03	16.05	0.06
48......	540	773	0.09	15.54	0.04

this dense cluster environment. Although these are at the bright end of the luminosity function of Sarajedini & Da Costa (1991), similar blue stragglers have been found in the centers of 47 Tuc by Paresce et al. (1991) and Guhathakurta et al. (1992), NGC 6397 by Lauzeral et al. (1992), and NGC 6681 by Watson et al. (1994).

Nevertheless, the proximity of the brightest of these stars to the horizontal branch suggests that we might contemplate a later stage of evolution for some of these stars. Binary mass transfer can yield low core mass helium-burning stars (Iben & Tutukov 1988) and a core mass 0.1 $M_{\odot}$ below the value expected at the He core flash would be capable of displacing a horizontal branch star into the observed location in Figure 2 according to equation (6) of Iben (1974). Stryker (1993) does not favor evolved star hypotheses for blue stragglers, remarking that there are spectroscopic criteria (surface gravity), which tend to argue for normal main-sequence status. It would be interesting to obtain spectra of these four stars in NGC 7099. It is entirely possible that more than one mechanism acts to produce blue stragglers.

TABLE 2

CALCULATED ULTRAVIOLET COLORS AND MAGNITUDES

log $T_{\rm eff}$ (1)	log L (2)	log g (3)	160 (mag) (4)	555 (mag) (5)	160–555 (mag) (6)
4.2844......	1.3088	4.95	−0.04	+3.34	−3.38
4.2362......	1.3518	4.73	−0.09	+2.95	−3.04
4.1907......	1.4053	4.51	−0.12	+2.49	−2.61
4.1424......	1.4658	4.27	−0.09	+1.98	−2.07
4.0913......	1.5224	4.03	−0.08	+1.65	−1.72
4.0398......	1.5701	3.79	+0.16	+1.22	−1.06
4.0144......	1.5905	3.67	+0.30	+1.06	−0.77
3.9897......	1.6088	3.56	+0.37	+0.97	−0.60
3.9658......	1.6254	3.45	+0.81	+0.79	+0.02
3.9427......	1.6404	3.35	+1.00	+0.71	+0.29
3.8989......	1.6663	3.17	+2.27	+0.57	+1.70
3.8585......	1.6882	2.99	+3.23	+0.54	+2.69
3.8220......	1.7069	2.84	+4.24	+0.54	+3.70
3.7712......	1.7376	2.63	+5.76	+0.55	+5.21
3.7557......	1.7623	2.57	+6.48	+0.53	+5.96
3.7466......	1.7832	2.53	+6.46	+0.47	+5.98
3.7432......	1.8018	2.52	+6.42	+0.43	+5.99

5. THE RADIAL PROFILE

Figure 4 shows radial number density profiles for the stars in Figure 2. The center was determined as the light centroid of the F555W frame. The error bars in Figure 2 are 1 σ uncertainties. The slope of this density profile is consistent with that obtained by Yanny et al. (1994) for stars with $V < 19.5$. We estimate that we have reproduced their centroid within a pixel.

The literature contains extended discussion of anomalies in the color profile of NGC 7099. With *IUE* Caloi et al. (1984) noted a pointlike UV source in the center of the cluster. The object is actually a composite of several red giants, several HB stars, and one BS star (see Fig. 3 of Yanny et al.). WFPC2 detects the HB star in F160BW. Caloi et al. note "one could suspect the object being embedded in thick nebulosity, but this has to be taken much more as a hypothesis than a suggestion." The nebulosity is caused by the blend. Many of the "objects" in their image are actually blends at 1″ resolution. Piotto, Djorgovski, & King (1988) debated the significance of a radial gradient in the sense of a central excess of blue stars. When Figure 2 is segregated into blue stars and red stars (e.g., at zero color), there is no statistically significant radial trend in the red to blue ratio. Figure 2 shows no extreme blue HB stars. This suggests that such radial color trends as may be present in NGC 7099 are confined to magnitudes fainter than the HB and are probably due to the blue stragglers, as indeed Yanny et al. have found. This is consistent with standard ideas of how blue stragglers form.

6. SUMMARY

We have obtained far-UV images of the globular cluster NGC 7099. We easily resolve all of the hot HB stars in the field, down even into the center of the cluster. We have constructed a far-UV to visible color–magnitude diagram for the hot HB and find no evidence for hot descendants

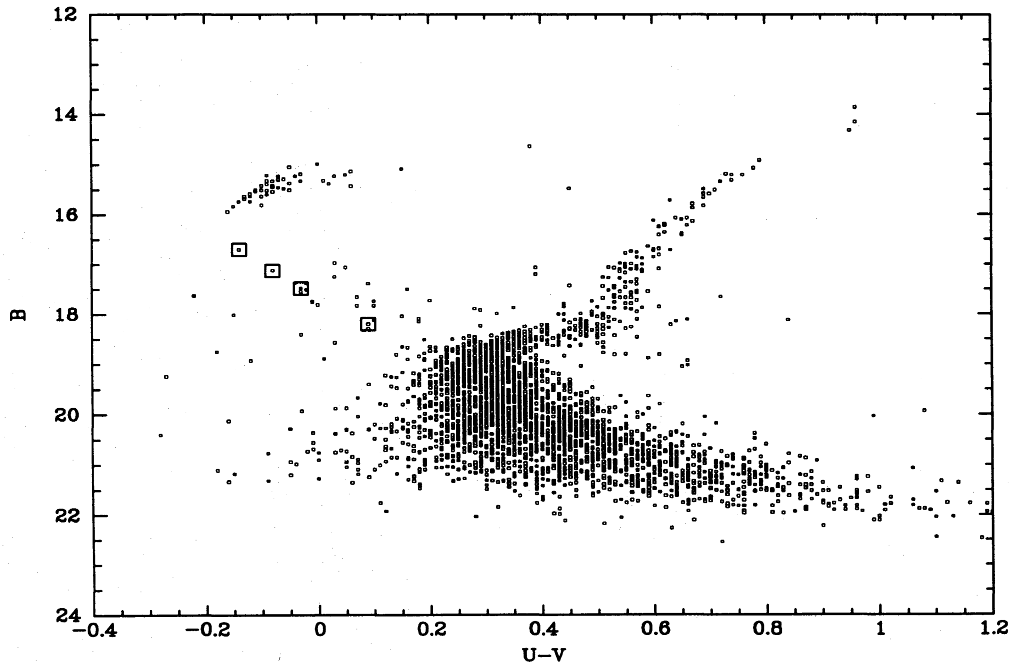

FIG. 3.—Optical color-magnitude diagram of the inner part of NGC 7099, from Yanny et al. (1994). The four blue stragglers discussed in § 4 are the stars in the boxes.

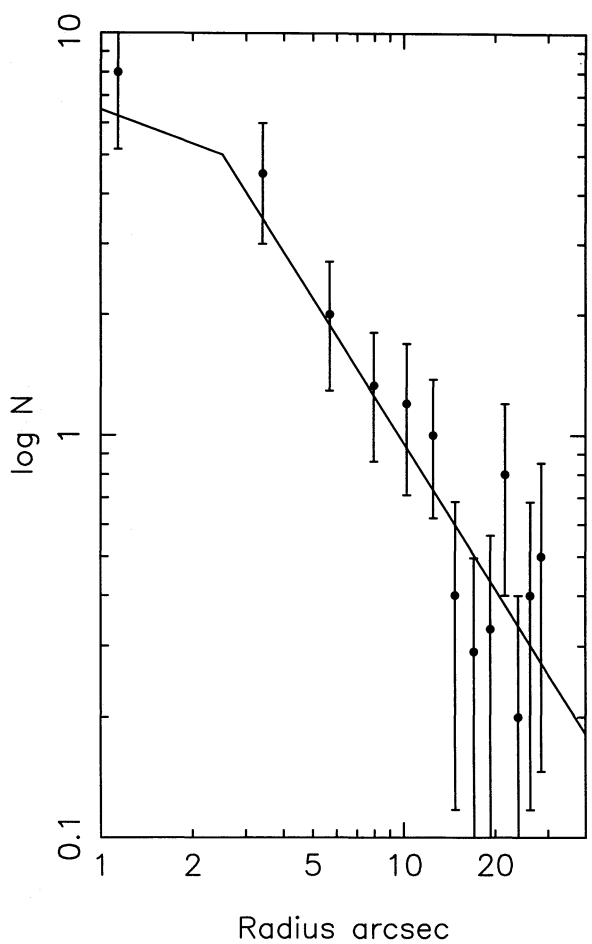

FIG. 4.—Radial density profiles for NGC 7099. The two line segments are the fit to the optical radial density profile by Yanny et al. (1994) normalized to the present FUV star counts.

beyond core He exhaustion. Luminous blue stragglers, however, stand out clearly in this diagram. The proximity of the brightest of these to the horizontal branch suggests that in some cases a core helium-burning evolutionary status may be relevant.

Our results are consistent with previous studies of the structure of this cluster, but in the HB there is no evidence for any color gradient.

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